

REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-01-

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not have a valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 12-26-00		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 1997-2000	
4. TITLE AND SUBTITLE Final Report to the Air Force Office of Scientific Research "Nonlinear Dynamics and Control of Wings and Panels"				5a. CONTRACT NUMBER F496F20-97-1-0414	
				5b. GRANT NUMBER 313-6021	
				5c. PROGRAM ELEMENT NUMBER NA	
6. AUTHOR(S) Earl H. Dowell Robert L. Clark, Jr. Lawrence N. Virgin				5d. PROJECT NUMBER NA	
				5e. TASK NUMBER 3484 / WS	
				5f. WORK UNIT NUMBER NA	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Duke University Mech. Eng. and Materials Sciences Pratt School of Engineering P.O. Box 90300 Durham, NC 27708				8. PERFORMING ORGANIZATION REPORT NUMBER NA	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research 801 N. Randolph Street Arlington, VA 22203				10. SPONSOR/MONITOR'S ACRONYM(S) AFOSR	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) NA	
12. DISTRIBUTION / AVAILABILITY STATEMENT NA					
13. SUPPLEMENTARY NOTES NA					
14. ABSTRACT Experimental and theoretical studies of the nonlinear dynamics and control of aeroelastic systems including airfoils and wings have been conducted. Nonlinear geometric stiffness and freeplay have been considered specifically and good theoretical / experimental correlation obtained. Active control systems have been designed, built and tested to increase flutter speed and reduce limit cycle oscillations (LCO).					
15. SUBJECT TERMS Aeroelasticity, Nonlinear Dynamics, Control, Flutter, Limit Cycle Oscillations (LCO)					
16. SECURITY CLASSIFICATION OF: NA			17. LIMITATION OF ABSTRACT NA	18. NUMBER OF PAGES 6	19a. NAME OF RESPONSIBLE PERSON Earl H. Dowell
a. REPORT NA	b. ABSTRACT NA	c. THIS PAGE NA			19b. TELEPHONE NUMBER (include area code) 919-660-5302

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFOSR)
NOTICE OF TRANSMITTAL DTIC. THIS TECHNICAL REPORT
HAS BEEN REVIEWED AND IS APPROVED FOR PUBLIC RELEASE
LAW AFR 190-12. DISTRIBUTION IS UNLIMITED.

FINAL REPORT TO THE
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
"NONLINEAR DYNAMICS AND CONTROL
OF WINGS AND PANELS"

AFOSR GRANT NUMBER F496F20-97-1-0414

Earl H. Dowell, PI
Department of Mechanical Engineering and Materials Science
School of Engineering, Duke University, Durham, N.C.

Robert L. Clark, Jr. CO-PI and Lawrence N. Virgin, CO-PI
Department of Mechanical Engineering and Materials Science
School of Engineering, Duke University, N.C.

November, 2000

OBJECTIVE

To develop a more fundamental understanding of the causes and modifications of limit cycle oscillations and other dynamic and control phenomena arising from nonlinear effects in aeroelastic systems. A combined experimental-theoretical study was pursued to validate and improve our physical understanding and mathematical models for design and analysis to enable flight of aircraft safely and reliably beyond the conventional and traditional flutter boundary.

RELATIONSHIP AND IMPORTANCE TO AFOSR

Some current Air Force flight vehicles are known to undergo limit cycle oscillations (LCO) due to as yet undetermined nonlinearities. If the source of these nonlinearities can be identified and accurately modeled mathematically, then such effects can be predicted and exploited in the design phase of new aircraft and/or modified existing aircraft. More specifically we know empirically through flight experience that some LCO can be tolerated without compromising mission performance while other LCO cannot. By developing an improved understanding and predictive capability for LCO, then it may be possible to design aircraft to operate safely and reliably beyond the conventional linear flutter boundary. This will lead to enhanced mission capability as well as increased flight safety.

BASIC RESEARCH ISSUES

The likely aerodynamic and structural nonlinear mechanisms are several. For the flow field, viscous effects leading to separation and/or compressible effects leading to shock waves may create a nonlinear relationship between the structural motion and the fluid response, e.g. the pressure acting on a wing or panel. Structural nonlinearities of interest include freeplay in the attachments between airframe elements, e.g. the control surface and the wing. Freeplay

20010406 173

leads to a bi-linear stiffness, i.e. a very low stiffness for small amplitude motions and a much larger, nominal stiffness (the ideal stiffness without freeplay) at larger amplitudes. Also the wing itself may have geometric nonlinearities arising from coupling between in-plane and out-of-plane structural motion. This coupling creates a nonlinear tension stiffening induced by in-plane stretching of the wing as a consequence of wing bending.

Until recently none of these nonlinear mechanisms has been subject to a systematic theoretical/experimental investigation to assess the importance of each of the several nonlinearities and our ability to model them accurately. Such a study was conducted with the support of the present grant.

APPROACH AND STATUS OF EFFORT

The focus of the present grant has been on structural nonlinearities as they affect the total aeroelastic system behavior, rather than studying aerodynamic nonlinearities. This is for two reasons. One is that aerodynamic nonlinearities are being addressed in a companion grant and the other is that the structure is a more likely candidate for making design choices to create desirable nonlinear effects and to avoid undesirable ones.

In the first phase of our work we have examined a prototypical model of an airfoil with a control surface attached. The attachment has a nominal linear spring stiffness behavior, but also incorporates a freeplay nonlinearity. An experimental model was built and tested in the Duke wind tunnel and the experimental results for LCO were correlated with those of a mathematical model that included the structural nonlinearity and a linear aerodynamic model. The correlation was very good for LCO response including amplitude and frequency of the motion. A transition from one type of LCO to another was predicted theoretically and observed experimentally. More recent work has shown the effectiveness of various control approaches in modifying or eliminating LCO and also investigated more deeply the nature of the several types of LCO that may occur and the transition from one to another.

In Figure 1 a sketch of the airfoil with freeplay is shown and a typical correlation of theory and experiment for LCO response as a function of flow velocity is presented in Figure 2.

Another prototypical model used in the grant work has been a low aspect ratio delta wing that has been constructed for experimental study. This wing model is of constant thickness and has the structural behavior of a plate (as distinct from a beam/rod). The structural nonlinearity is the tension induced by bending discussed above. Again theoretical/experimental correlation has been good. Our most recent results are for the delta wing placed at a steady angle of attack. The steady angle of attack gives rise to a steady loading on the wing that deforms the wing statically, thereby changing the effective linear stiffness as well as the nonlinear stiffness of the wing structure. Two significant theoretical predictions have been made. On the one hand, the flow velocity for the onset of the LCO (i.e. the flutter speed) is reduced by increasing the angle of attack, but on the other, the amplitude of the LCO is also reduced. So there is both a positive and a negative impact of a non-zero angle of attack. We plan to investigate these interesting and important predictions experimentally in future wind tunnel tests. Also future tests will examine the

effects of various control methods and investigate the nature of the LCO in more depth, for example changes of flutter mode shape with airspeed.

In Figure 3 a sketch of the delta wing model is shown and a typical correlation of experiment and theory for LCO response as a function of flow velocity (for zero angle of attack) is presented in Figure 4.

As another phase of our work we are considering the effects of gust loading on both the airfoil and wing models. For linear systems the effects of flutter and gust response may be considered separately, but for nonlinear systems there is a nonlinear interaction between gust excitation and LCO and thus simple linear superposition no longer applies.

SIGNIFICANT RESULTS AND ACCOMPLISHMENTS

A deeper understanding of two prototypical structural nonlinearities on LCO has been obtained. This suggests that reliable and practical analysis and design methods can be developed, not only for the relatively simple models investigated here which contain the fundamental physics for such nonlinearities, but also for the more complex structures encountered in flight vehicles.

Specifically, it has been shown experimentally and theoretically that aeroelastic systems may be operated safely beyond the onset of LCO and their responses predicted accurately and reliably for the nonlinearities investigated here.

ACKNOWLEDGMENT/DISCLAIMER

This work was sponsored (in part) by the Air Force Office of Scientific Research, USAF, under grant/contract number F496F20-97-1-0414. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Office of Scientific Research or the U.S. Government.

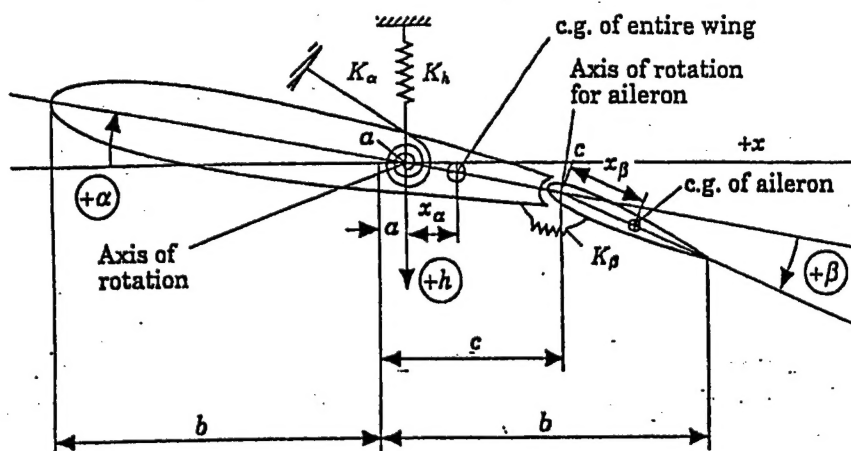
PUBLICATIONS

1. Conner, M.C., Virgin, L.N. and Dowell, E.H., "A Note on Accurate Numerical Integration of State-Space Models for Aeroelastic Systems with Freeplay", AIAA Journal, volume 34, 1996, pages 2202-2204.
2. Conner, M.C., Tang, D.M., Dowell, E.H. and Virgin, L.N., "Nonlinear Behavior of a Typical Airfoil Section with Control Surface Freeplay: A Numerical and Experimental Study", Journal of Fluids and Structures, volume 11, 1997, pages 89-109.
3. Tang, D.M., Dowell, E.H. and Virgin, L.N., "Limit Cycle Behavior of an Airfoil with a Control Surface", Journal of Fluids and Structures, volume 12, 1998, pages 839-858.

4. Tang, D.M., Conner, M.C. and Dowell, E.H., "Reduced Order Aerodynamic Model and Its Application to a Nonlinear Aeroelastic System", Journal of Aircraft, volume 35, 1998, pages 332-338.
5. Tang, D.M., Dowell, E.H., and Hall, K.C., "Limit Cycle Oscillations of a Cantilevered Wing in Low Subsonic Flow", AIAA Journal, volume 37, 1999, pages 364-371.
6. Tang, D.M., Henry, J.K. and Dowell, E.H., "Limit Cycle Oscillations of Delta Wing Models in Low Subsonic Flow", AIAA paper 99-1460, 1999.

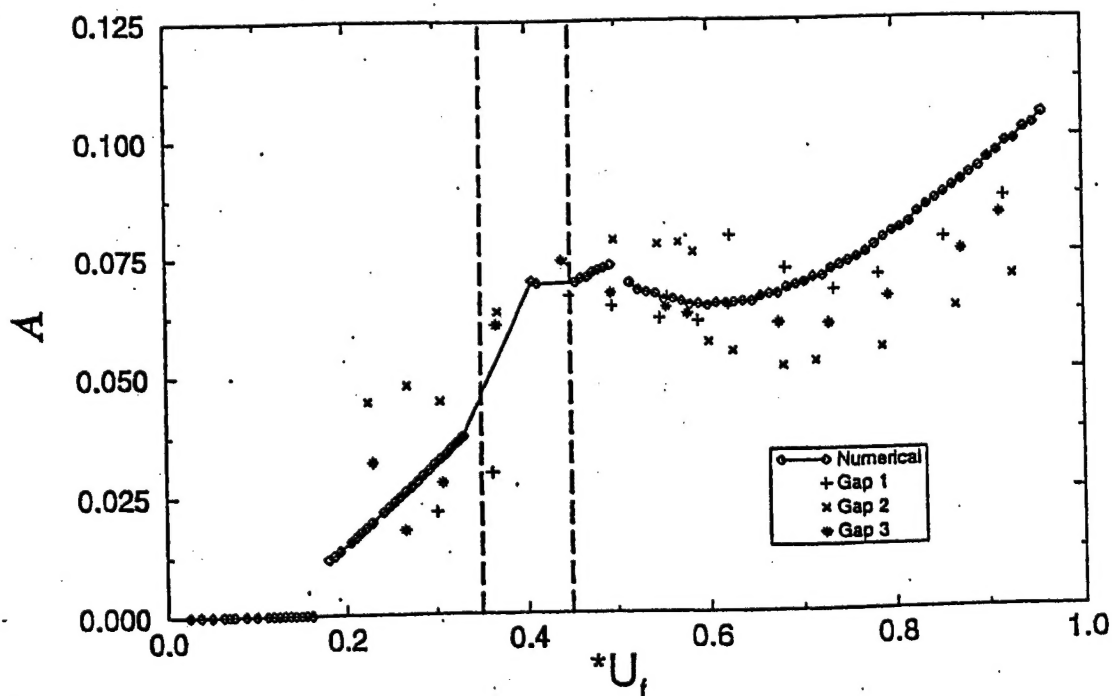


Figure 1



SKETCH OF THE AEROELASTIC TYPICAL SECTION WITH CONTROL SURFACE.

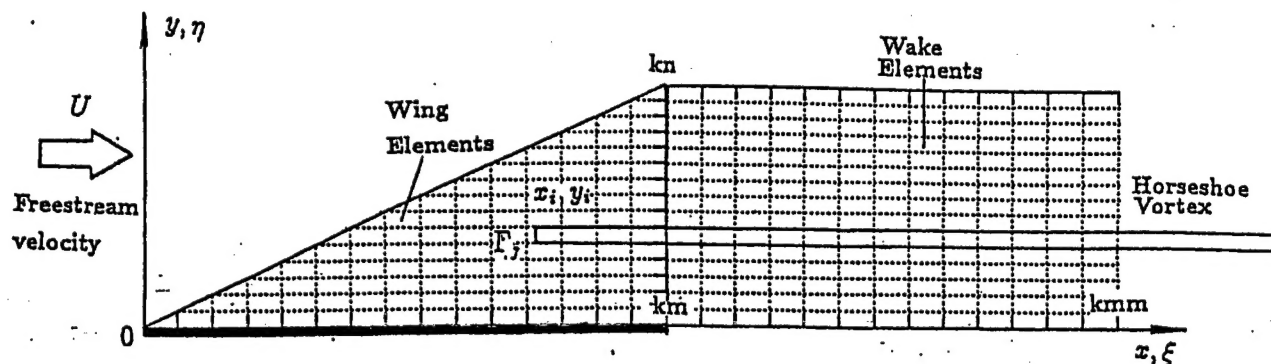
Figure 2



Numerical (lines) and experimental (points) normalized steady-state RMS amplitude for pitch vs. Flow Velocity

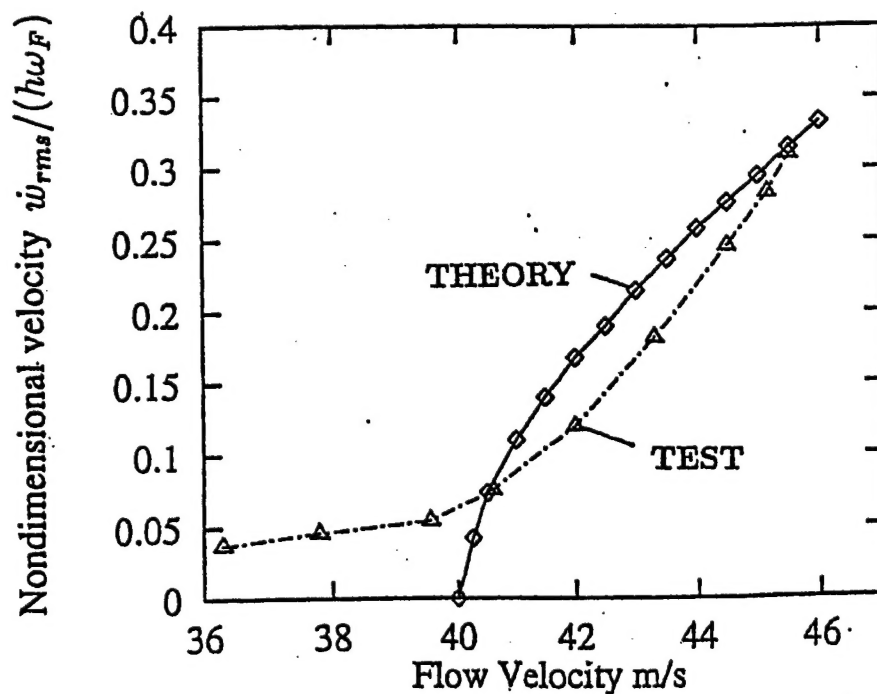


Figure 3



SKETCH OF THE AEROELASTIC MODEL OF A DELTA WING

Figure 4



Theoretical and experimental nondimensional transverse velocity vs. Flow Velocity